PHASE I – JUST-IN-TIME MAINTENANCE OF NUCLEAR POWER PLANTS

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Just-In-Time Maintenance of Nuclear Power Plants
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Overall Project Goal

The goal of this project is to develop and demonstrate the feasibility of a new technology for maintenance engineering: a Just-In-Time Maintenance (JITM) system for rotating machines. The JITM system is based on several key developments at Texas A&M over the past ten years in emerging intelligent information technologies, which if integrated into a single system could provide a revolutionary approach in the way maintenance is performed. Rotating machines, such as induction motors, range from a few horse power (hp) to several thousand hp in size, and they are widely used in nuclear power plants and in other industries. Forced outages caused by induction motor failures are the reason for as much as 15% - 40% of production costs to be attributable to maintenance, whereas plant shutdowns caused by induction motor failures result in daily financial losses to the utility and process industries of $1 M or more. The basic components of the JITM system are the available machine sensors, that is electric current sensors and accelerometers, and the computational algorithms used in the analysis and interpretation of the occurring incipient failures. The JITM system can reduce the costs attributable to maintenance by about 40%, and it can lower the maintenance budgets of power and process plants by about 35%, while requiring no additional sensor installation. As a result, the JITM system can improve the competitiveness of US nuclear utilities at minimal additional cost.

Summary of Overall Project Approach

As the electric utility industry is rapidly entering an era of deregulation, the survival of the nuclear generating units will highly depend upon their continued profitability. Minimizing and ultimately eliminating unplanned outages, and extending the time period between planned (or maintenance) outages can greatly enhance the economic performance of a nuclear power plant. In fact, in order to enhance their profitability some nuclear utilities are already contemplating to extend the nuclear fuel cycle from 18 months to 24 months. In electric power generation the failure of critical equipment like turbines, generators, motors, fans, and pumps costs millions of dollars in reduced output, emergency maintenance costs, and lost revenues. The utility industry's response to this risk has been to invest heavily in preventive, and more recently in predictive, maintenance. The importance of detecting problems and preventing failure is reflected in the fact that in many nuclear power plants 15 - 40 % of production cost is allocated to maintenance. Maintenance cost is, in fact, one of the highest controllable operational cost. A more reliable predictor of the maintenance requirements of critical machines would save nuclear utilities hundreds of millions of dollars per year in loss of revenues during downtime, overtime costs associated with emergency repairs, and disrupted generation schedules. A *Just-In-Time Maintenance* (JITM) system is what is envisioned by our team. Such a breakthrough technology might, perhaps, enable nuclear utilities to operate at sufficiently high profitability levels for a competitive power market, deferring a further down-turn in the industry.

Just-In-Time Maintenance Technology: JITM means taking a piece of equipment off-line for servicing when it needs it, rather than according to a fixed schedule. It is expensive and time consuming to shut down critical machines like motors, generators, pumps, fans and turbines for maintenance, so plant operators would like to be sure that the equipment needs servicing before they schedule it. Today, maintenance schedules are based on manufacturer's test data. Of course, no two machines are alike, so fixed maintenance schedules sometimes result in shutting down a machine before it really needs it, or in continuing to operate one that should be overhauled.

Prior federal research funds have been used to develop a novel neural network, as well as a neural network-based application that can detect incipient faults in motor-pumps at very early stages. The purpose of this motor-pump fault diagnosis system was to avoid the catastrophic failure of motors and pumps during power plant operation, and to provide operational data on demand to schedule preventive maintenance. Current industry standard diagnostic procedures are based on expert systems, or statistical studies that use idealized operational parameters as a guideline and are neither adaptable to individual machines, nor can they "learn" to identify the reason that roughly defined operational parameters have been exceeded. Tests on motor-pump data show that our algorithms, in fact, are not only able to predict failure with a high degree of confidence, but can also provide an operator with specific information as to what is wrong. This integrated neural network diagnostics system approach may represent a breakthrough in machine diagnostics because of the technology's ability to "learn" the operational characteristics of individual machines, and because the neural network can pinpoint the problem.

Phase 1 Objectives

The objectives of the Phase 1 part of the project, as defined in the original project proposal, are as follows:

1. ***Adapt the Information Processing Algorithms to Induction Motors:*** Run and test our existing neural networks, wavelets, and fuzzy logic algorithms on induction motor data (6/1/98, 5 months),
2. ***Adapt the Information Processing Algorithms to Synchronous Generators:*** Run and test our existing neural networks, wavelets, and fuzzy logic algorithms on synchronous generator data (6/1/98, 5 months),
3. ***Determine Prototype System Requirements:*** From the above algorithm testing, determine the sensor and channel requirements, and the sampling rate that will be necessary to support the prototype (4/1/99, 2 months).

Objectives Accomplished in Phase 1

All of the objectives set-forth in the Phase 1 part of the proposed project proposal have been accomplished to satisfaction.

Summary of Significant Research Results

In this section we summarize the most significant research results of the Phase 1 effort.

Preliminary Motor and Generator Results

A few selected results are presented based on the Phase 1 tasks. Initially, the results from motor speed estimation are presented. One such set of results, shown in Figure 1, depicts the results of the neural network speed estimation algorithm for 0-70% load change. The results are compared to speed estimates obtained by the extraction of harmonics from electric current measurements. The average estimation error is about 3 rpm, with the peak error at 7.5 rpm. Figure 2 depicts the results of the speed estimation algorithm in the event of two broken rotor bars. The average error is about 2.2 rpm and the peak error is about 13 rpm. Finally, in Figure 3, a set of comparative speed estimation results is depicted. First the generator speed signal is shown, followed by the de-noised speed estimate and the neural network speed estimate. The signal de-noising is performed using a wavelet-based algorithm. Also shown are the speed measurements obtained by a hand-held tachometer.

Hardware Set-up Prototype Requirements

Based on our preliminary analysis, it is envisioned to have the hardware set-up with three fundamental sections (motor, gearbox, and pump) coupled with conventional shaft couplings. The requirements of the hardware set-up have been defined as follows:

Motor:

- One horsepower, three phase induction motor with a maximum rated speed of about 1780 rpm.
- The end belts will be removed and an independent, adjustable bearing support will be provided at each end to secure the rotor. This will enable one to introduce parallel and angular misalignment from end-to-end. Of course, the small rotor to stator air gap restricts the amount of permissible misalignment. The bearings will be replaceable so that simulated bearing faults can be introduced.
- The rotor will be replaceable so that a defective rotor such as poor balance, broken rings and bow can be introduced.
- The stator will be secured to the motor housing, which the machine frame will support. The simulation of winding defects such as shorted end-turns and stator sag are possible, but this would require some modification.
- Provision will be made to mount transducers on the bearing supports and the stator housing for vibration studies. Tri-axial acceleration readings will be obtained at both bearing housings.

Regarding the introduction of actual electrical faults, some additional analysis will be needed to calculate the staged faults being staged.

Controller:

- A standard industrial quality inverter would be provided to permit speed changes.
- Relocating leads on a terminal block would permit powering the motor directly from a three-phase voltage source or from the controller. The same terminal block can be used to access voltages and currents on all three phases.

Speed and Torque Sensors:

- Provision will be made to monitor speed and torque between the motor and the gearbox. Some additional analysis will be needed to determine the type of the speed and torque sensors to be installed.

Gearbox:

- The gearbox will be a parallel shaft reducer with two gears. The gears will be accessible for introducing defects. Gears can be provided with damaged teeth, missing teeth, and worn teeth. Since this is not a standard gearbox, some additional analysis will be needed prior to installation. Bearings will be replaceable.

- Provision will be made to mount transducers for vibration studies. Tri-axial acceleration readings will be obtained at both bearing housings.

Pump:

- To best simulate a real load, a centrifugal style liquid pump will be employed. Since the liquid (say water) is relatively incompressible, the pulsation from the vanes as they pass the cutwater will be prominent in the vibration spectrum.
- The pump system will have a pump, discharge valve for adjusting the back pressure, head tank, and valve on the pump suction for introducing cavitation. Instrumentation will include a discharge pressure gauge and suction pressure gauge. Additionally, a flow meter will be added. Typical fault simulations could be a missing impeller vane, a damaged impeller vane, and cavitation.
- Provision will be made to mount transducers for vibration studies. Tri-axial acceleration readings will be obtained at both bearing housings.

The test-bed with the aforementioned requirements will be assembled and tested in Phase 2 of the project.

Project Related Accomplishments

Graduate Student Theses and Dissertations

The following graduate dissertations are being pursued with funds from this project:

1. R. M. Bharadwaj, "Adaptive Nonlinear State Filtering for Electric Machine Speed Estimation," PhD Dissertation, in progress.
2. H. Kim, "Model-Based Fault Diagnosis of Electric Machines Using Neural Networks," PhD Dissertation, in progress.
3. S. Nandi, "Fault Analysis of Electric Machines for Condition Monitoring," PhD Dissertation, in progress.

Journal Papers

The following journal publication has resulted from research that is related to this project:

1. Nandi, S., H. A. Toliyat, and A. G. Parlos, "Performance Analysis of a Single-Phase Induction Motor Under Eccentric Conditions," submitted to the IEEE Transactions on Industry Applications, August 1998.

Conference Papers

The following conference publications have resulted from research that is related to this project:

1. Nandi, S., Toliyat, H. A., and Parlos, A.G., "Performance Analysis of a 3-Phase Induction Motor Under Mixed Eccentricity Conditions," Second International Conference on Power

Electronics, Drives and Energy Systems for Industrial Growth, Perth, Australia, November 30 – December 3, 1998.

2. Bharadwaj, R, A. G. Parlos, H. A. Toliyat, and S. K. Menon, "A Neural Network-based Speed Filter for Induction Motors: Adapting to Motor Load Changes," Proc. of the International Joint Conference on Neural Networks, Washington, D.C., June, 1999.
3. Bharadwaj, R, A. G. Parlos, H. A. Toliyat, and S. Nandi, "A Neural Network-based Speed Filter for Induction Motors: Adapting to Motor Condition Changes," IEEE International Conference on Diagnostics for Electrical Machines, Power Electronics, and Drives, Dijon, Spain, September, 1-3, 1999.

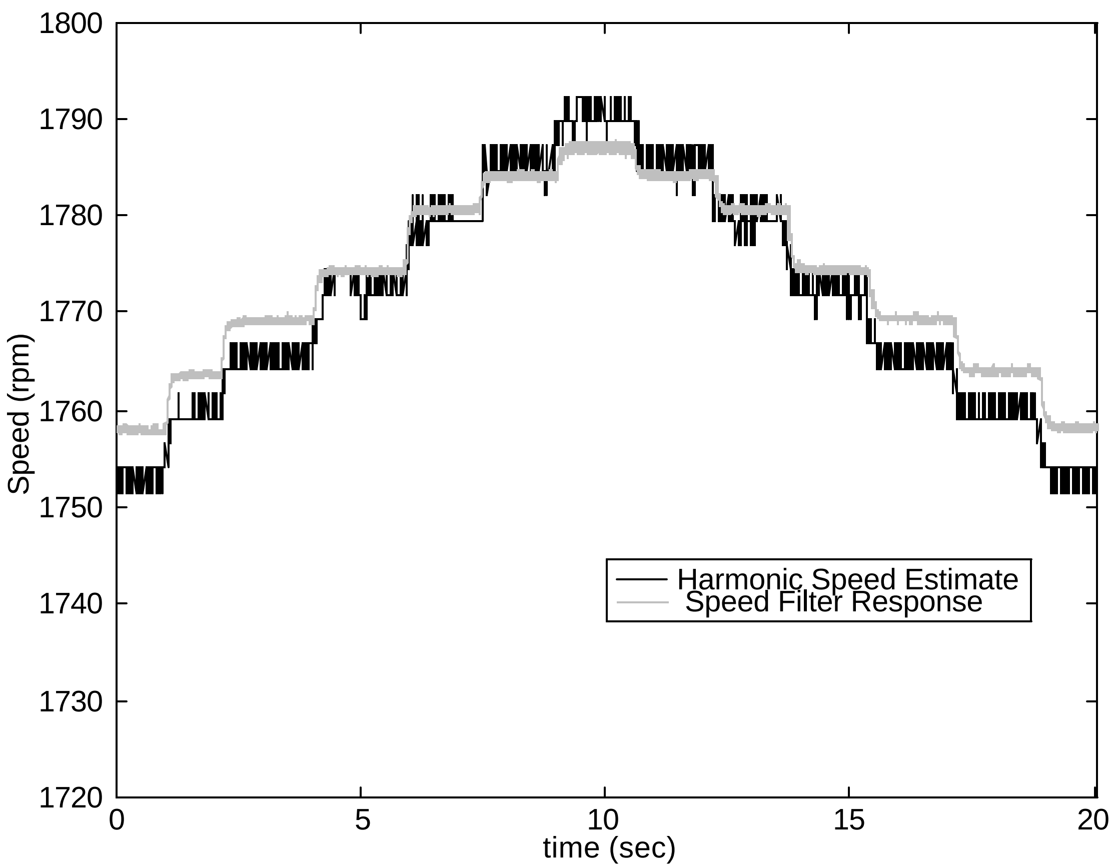

Figure 1. Neural network filter response for 0-70% load change using rotor 1.

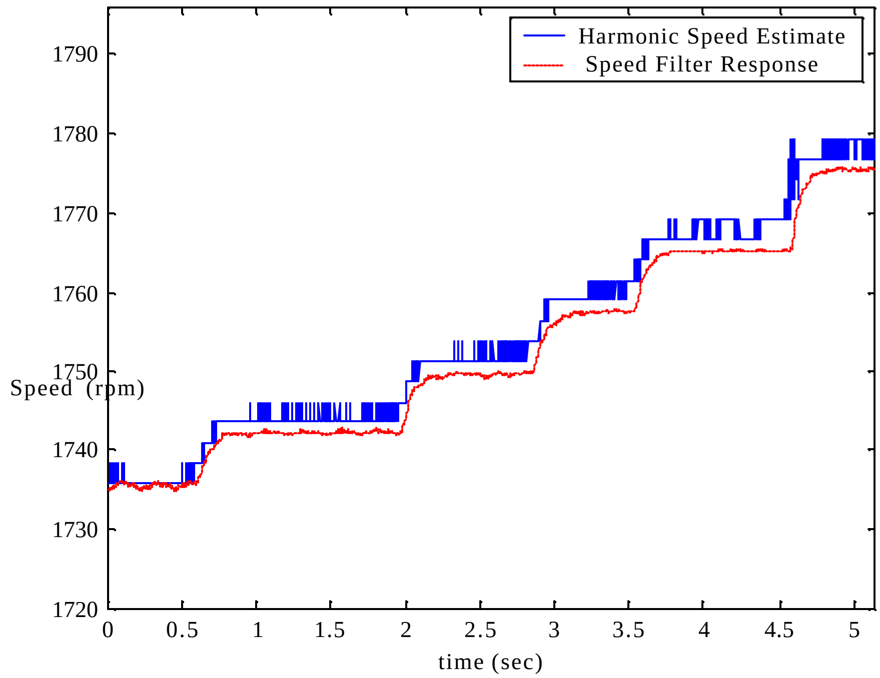

Figure 2. Neural network speed filter response for two rotor broken bars scenario.

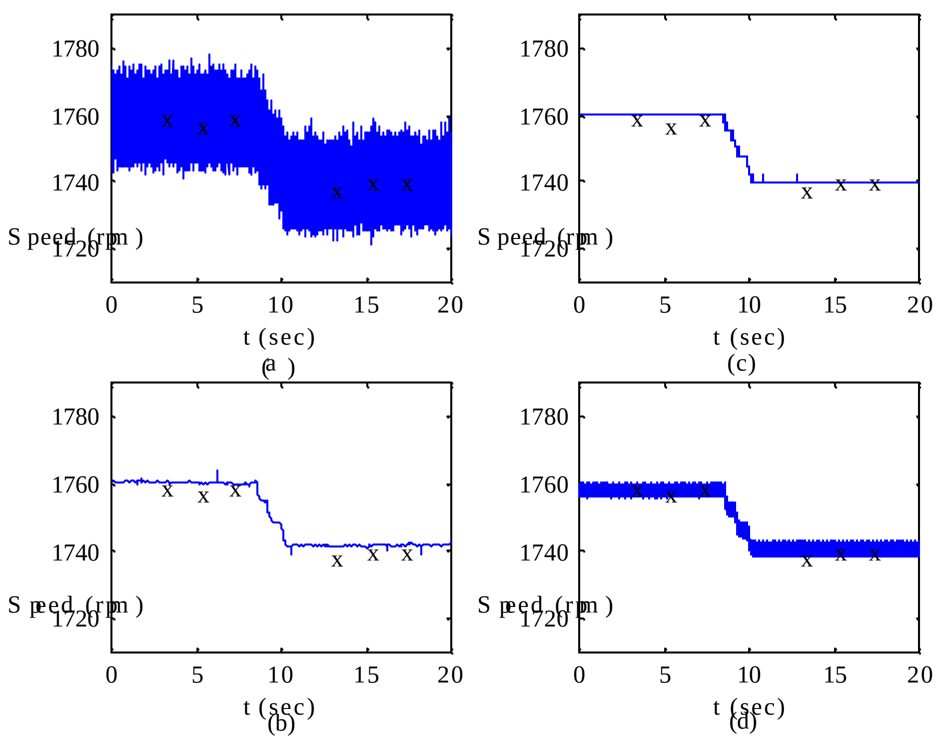

Figure 3. Speed of motor: (a) generator speed signal, (b) de-noised speed signal, (c) shifted-RSH based speed estimate, (d) neural network speed filter response, the ‘x’ represent the hand-held tachometer reading.